Enhancing Telemetry and Navigation Performance with Full Spectrum Arraying

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Abstract— At the start of the new millennium, a new array capability will be introduced into the NASA Deep Space Network (DSN). This is a second generation system employing the full spectrum combining technique first deployed to support the Galileo mission in 1996. The new array capability offers multi-mission support with real-time combining at higher data rates. In addition, for the first time in the DSN history, it is now possible to array ranging signals to enhance navigation performance.

With the enhanced signal-to-noise (SNR) obtained from an effectively larger aperture, the array enables support to missions whose signal level falls below the tracking threshold of a single antenna. Alternatively, it can also be used of increase the data return over that possible with a single antenna. To the extreme extent, the array deployment at Goldstone can offer substitution of the 70-meter antenna with an array of four 34-meter antennas.

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1. INTRODUCTION

Arraying is a common technique used to improve reception of weak signal. It is symbolically demonstrated in Figure 1. The signals received simultaneously from different antennas are combined, creating the same effect of an enlarged aperture. This application is beneficial in deep space communications where the spacecraft signal is severely attenuated as it travels across the vast interplanetary distance.

Starting in 2000, a new array capability of multi-mission support nature will be introduced into the NASA Deep Space Network. Specifically, the Goldstone facility in California - one of the three DSN sites located around the world to provide 24-hour coverage - will have the capability to array up to eight antennas.

This paper first provides a historical context on the application of arraying. It then follows with a description of developed system and highlights on different aspects of signal processing. Also presented is the result obtained from field measurement.

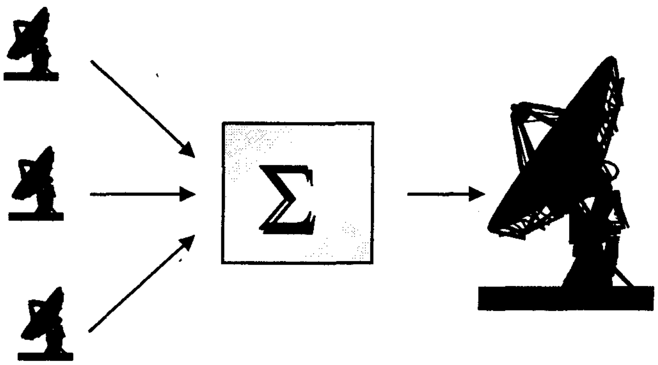

Figure 1 Benefit of arraying

2. PAST AND FUTURE USE OF ARRAY

In the past, Voyager mission relied on arraying to increase its data return during the 1986 Uranus encounter. Galileo mission is another recent example wherein arraying was used to significantly increase the science data return. Galileo arraying employed up to five antennas, located at three different tracking facilities and spread over two continents of North America and Australia. The arraying resulted in an increase of a factor of 3 improvement in data return.

Future missions can also benefit from arraying. These

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include the class of mission whose certain phase of operations requires more performance than what being offered by a link of single antenna. For example, Cassini mission requires only single 34-meter support during cruise period, yet upon entering Saturn orbit, in order to return 4 Mbits/day mapping data, it requires the use of an array of a 70-meter and 34-meter antennas.

Another class of potential user is missions that need to relay back to Earth critical science data from critical observation in a short amount of time as possible in order to avoid data loss due to possible future mishap. Stardust belongs to this group of customers. Upon encountering the Wild 2 comet in 2004, the mission likes to reduce the single-event risks by sending data back as fast as possible. An array of two 34-meter antennas will enable Stardust mission to cut the transmission time in half, over the single-antenna baseline.

In the DSN, the 70-meter antenna, being the largest tracking station, is often relied on for tracking spacecraft in the outermost region of deep space. This antenna, however, was built more than 20 years ago. As the antenna structure ages and requires more maintenance service, there is a growing concern regarding its availability. An array of several smaller 34-m antennas can serve as a substitution for the 70-meter during extended maintenance downtime.[1]

Another way of looking at the issue is that arraying increases the flexibility of DSN scheduling and allows for better utilization of available resource. In the absence of array capability, a shortfall in 34-meter link performance would require the use of the 70-meter. As a result, there exists a potential for over-subscription of the 70-meter antenna service. With array, however, the DSN has the option to schedule additional 34-meter antenna incrementally to meet the mission need. Figure 2 provides a comparison on the relative performance of different array configurations.

[1] It should be noted that the 70-m substitution, or other array usage discussed in this paper, refers only to downlink processing. The capability, as built, does not support an arrayed uplink.

Figure 2 Relative performance of array

3. MERITS OF FULL SPECTRUM ARRAYING

The main objective of array is to coherently combine signals from different antennas; however, because the antennas are geographically separated, the signal received at each site has a different delay and Doppler signature which is dependent on the antenna's position and motion relative to the spacecraft. The differential delay and Doppler need to be removed so that all data streams are aligned.

The signal used in deep space communications typically comprises of three components: a sinusoidal carrier, a square sub-carrier and telemetry symbols. The process of cross correlation and combining can be done the level of symbol, carrier or across the whole spectrum. Figure 3 illustrates the three different schemes. The array implementation described in this paper employs the full spectrum method. In the following paragraphs, we'll highlight the relative merits between this technique and other traditional ones.

Figure 3 Different array methods - symbol, carrier and full spectrum.

Symbol Combining

In symbol combining, demodulated symbols from different antennas are cross correlated, delay compensated and finally combined. The resulting signal has a higher energy per bit to noise spectral density (Eb/No), thus allowing a lower bit error rate performance. Thus, the combined signal allows for proper decoding of telemetry information whereas individual symbol streams would not. Historically, this technique was used in Voyager mission.

The symbol combining technique offers an advantage of doing signal processing at relative low symbol rate, typically in the range of tens of kHz. Requirement on the accuracy of data alignment is therefore less constrained. Transporting of symbol streams to be combined over long distance is also easy, thus, allowing antennas at large distance to participate in the array.

The drawback, however, is that it requires signal level at individual antenna to be sufficiently high to ensure proper symbol demodulation. Otherwise, valid symbols can not be derived.

Carrier arraying

In carrier arraying, information of the carrier signal detected at the main antenna is used to achieve acquisition at the supporting antenna. Once both receivers lock up, symbol streams can then be combined.

The advantage of carrier array is that it reduces the signal threshold required for normal operation at supporting antennas; however, the array reference still needs to be able to acquire the signal on its own.

Full spectrum combining

In full spectrum combining, the entire signal spectrum of interest that contains the carrier, sub-carrier and symbol, is combined all at once. Ranging signal sharing the signal spectrum is also combined. The result is an improvement in radiometric observable as well. Carrier demodulation, also sub-carrier and symbol synchronization, takes place only after signals are combined. This main advantage, thus, is a lowering of acquisition threshold required in the receiver, decoder and ranging correlator.

The challenge of spectrum combining is in the correlation process. The error in the estimation of relative delay between pair of antennas becomes more pronounced since processing now applies to IF frequency, which is higher than symbol frequency.

Full spectrum arraying was first employed in Galileo mission. The Galileo support equipment, however, is tailored to low data rate (below 1 ksym/s). The new capability described in this paper extends the supported data rate to 6 Msym/sec. Unfortunately, because of the real-time nature of processing at these high data rate, the array is limited to those antennas within a tracking complex, i.e., no inter-complex arraying across two continents as in the case of Galileo arraying.

In summary, symbol combining is achievable as long as individual antennas in the array can acquire and demodulate the signal. Its benefit, thus, applies mostly to the decoding process. Carrier arraying helps to overcome the shortfall in the receiver carrier tracking loop at the supporting antennas. Full spectrum arraying further reduced the required threshold, enabling proper demodulation of the combined signal although such processing can not be done at individual antennas..

4. EQUIPMENT DESCRIPTION

Signal processing for arraying is performed by two main assemblies - Full Spectrum Receiver (FSR) and Full Spectrum Combiner (FSC), see Figure 4. The FSR input are individual 300 MHz IF signal that has been amplified and downconverted after captured by the antenna. Once digitally combined in the FSC, the signal is converted back to analog form. The combined signal now has the same characteristics as that arriving at the reference antenna, however, at a higher SNR. Downstream processing such as demodulation, decoding, and ranging detection can then be applied to yield final science and engineering data products.

TBS

Figure 4 Array signal processing equipment

Major components of the FSR are illustrated in Figure 5. The analog/digital converter and the digital downconverter capture relevant portion of 300 MHz IF analog signal in a 16 MHz 8-bit inphase and quadrature digital data streams. The delay line and phase rotator boards correct signal delay and phase using information from predicts and from feedback from FSC on residual effect. The signal monitor board samples the digital data streams and transform them to measurement of carrier and telemetry signal to noise ratios. These values are provided to operators for monitoring purpose. They are also relayed to the FSC for proper setting of the combining coefficients. Measurement of the carrier SNR is obtainable directly from the standard Fast Fourier transform. Measurement of the telemetry SNR, however, requires some manipulation involving the correlation of the upper and lower harmonics of the subcarrier. The Realtime and Data processors handle high-level monitor and controls in the FSR.

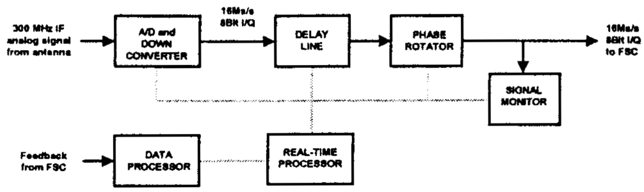


Figure 5 Processing in the full spectrum receiver.

Figure 6 presents major components in the FSC. The cross correlation of upper and lower sideband of different antennas are used to derive differential phase and delay values for feedback to the FSRs. At the same time, the Weight and Sum combines the weighted FSRs input, to produce optimal output. The D/A and Upconverter transforms the digital baseband stream to an analog 300 MHz IF. The Signal Monitor, Realtime and Data processors carry out functions similar to those in the FSR.

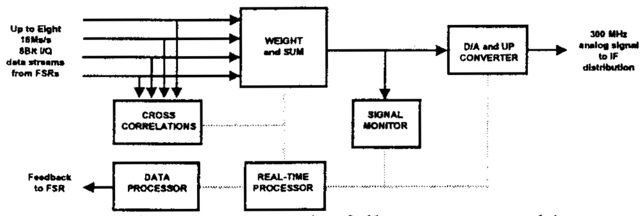


Figure 6 Processing in the full spectrum combiner

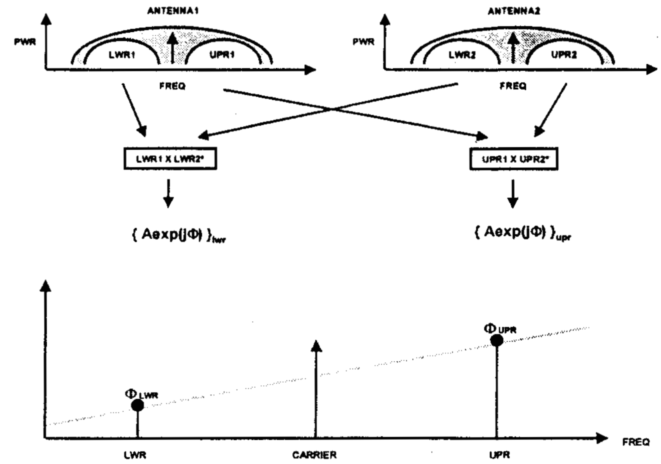
5. SIGNAL PROCESSING

This section highlights some aspects of signal processing used in arraying. Main focus is on the correlation, delay compensation and combining.

Correlation

Correlation is an essential process without which proper combining can not be done. This section addresses some certain aspects of correlation such as algorithm, integration time, etc.

Figure 7 shows the detail processing of correlation. With the aiding of Doppler predicts, the upper and lower sideband of the signal received at each antenna are captured. The upper sideband from one antenna is correlated with the same component of the array reference, from which the phase difference at upper sideband is measured. The same process is simultaneously applied to the lower sideband. An average of the two phase measurements then yields the relative phase offset, while the ratio of their difference to twice the sideband frequency provides the relative time delay.



PHASE ERROR $\sim= (\Phi_{LWR} + \Phi_{UPR}) / 2$

DELAY ERROR $\sim= (\Phi_{UPR} - \Phi_{LWR}) / (2 * \text{SIDEBAND FREQUENCY})$

Figure 7 Correlation procesing

There are different ways implementing the correlation. Two options were implemented in the array equipment, both are successfully tested. The simpler scheme fixes the array reference at one antenna, typically the one with the highest SNR. This scheme works well when one element of the array has a significant higher SNR than others, as in the case of arraying the 70-m and 34-meter antennas. The second method treats the reference as a rotating sum of all antennas except the one under consideration. In other words, one antenna will be cross correlated against the sum of all others. This applies to an array of all 34-meter antennas of similar SNR. Simulation results indicate that the rotating sum method performs better than the fixed reference, and that the final solution emerges within a few iterations, see Figure 8 *[1]*

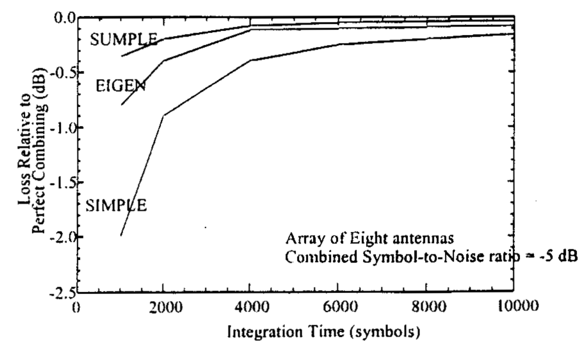


Figure 8 Different methods of correlation

Consideration also needs to be given toward the setting of integration time for the correlation. From the thermal noise consideration, long integration period is preferred since it would result in an estimate with small error. Obviously, the lower the signal level, the more integration time required.

The problem, however, is that the signals received at different antennas travel through the tropospheric regions, and therefore, subjected to different delay. These tropospheric delays vary on a shorter timescale. Long integration period would result in less correlation. An illustration of these two constraints is shown in Figure 9. The combined signal is assumed at -5 dB/Hz, all antennas of equal aperture with a 1-10km antenna baseline separation. Also assumed is a correlation phase error of no more than 20 deg. The shaded triangular area is the operating region bounded by two constraints - thermal and tropospheric noise. Note that the graph is actually expressed in term of symbol rate, rather than in signal to noise ratio. Given a fixed symbol SNR, these two quantities are equivalent.

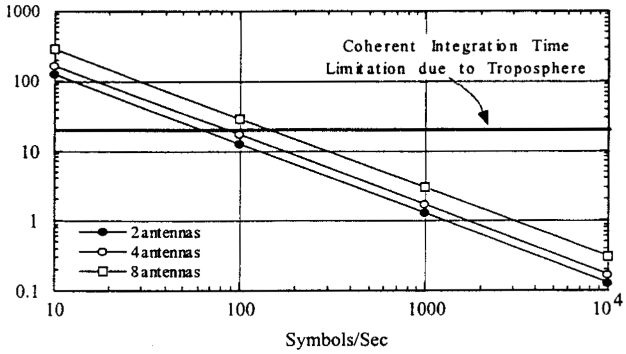


Figure 9 Limits of correlation integration time.

Care must also be given toward the use of correlation measurement. Invalid measurement can result because of problem with the inputs, e.g., antenna mispointing, planetary occultation, etc. As in any control feedback system, care must be given to the design so that bad estimation of the error signal would not drive the system away from the stable condition. A filter on the correlation estimates in the FSC allows a runaway condition to occur.

Delay compensation

The delay compensation process is done in two steps. First, each FSR is provided with two sets of delay predicts, one for reference antenna, the other itself. Using predicted information, the FSR removes the predicted differential delay so that its signal can be aligned with the reference. These predicts are computed based on the spacecraft trajectory and location of tracking antennas. Due to the long distance between spacecraft and Earth, most of the delay variation is due to Earth rotation. Once the signals flows to the FSC, residual error is measured and feedback to the FSR. The second step accounts for adjustment needed to be made based on the residual error measured in the FSC.

Over the track, the relative position of different antennas in the array changes, with respect to the spacecraft. The delay of non reference signal would vary relative to that of the reference. Part o the track it is closer to spacecraft, the rest farther. The relative delay is corrected by adjusting the physical delay line in the non-reference FSR. Since such adjustment is only possible with positive values, a bias needs to be introduced to all antenna. The bias is typically set at a value at least equal to the maximum delay among arraying antennas. Since now the combined signal is shifted in time by the introduced bias, the following telemetry and radiometric data needs to acc processing of telemetry and. The bias introduced in the combined IF signal is then compensated for in the follow-up telemetry and radiometric processing, by adjusting the reported received timetags of Doppler, ranging, and telemetry data.

One additional consideration is needed. In order to arrive at the correct relative delay between two antennas, both sideband and carrier information are needed. The reason is due to the 2π ambiguity in the phase difference from upper and lower sidebands. The sideband measurement alone can only point to a set of possible delays of $1/(2*f_{sb})$ modulo, where f_{sb} is the sideband frequency. Among these values, only the true delay yields a stable cross-correlated phase at carrier frequency. All others will result in the carrier phase being monotonically increased or decreased, in modulo of 2π.

Combining

Combining is done very much in a straight forward process. The 16-MHz samples from different FSRs are weighted according to the relative signal to noise ratio. The system allows provision to disable certain input where signal is not detected, so that the non-contributing element would not affect the gain performance.

6. RESULTS

Result of field demonstration at Goldstone with missions currently in flight is presented below. Specific focus will be placed on the array gain for telemetry and radiometric data.

Telemetry array gain

Figure 10 shows the measurements of individual SNR (data SNR, Pd/No, specifically) at each of the two 34-m antennas and at the combined signal during one of the Mars98 Climate Orbiter track on July 1, 1999. The profile vary as a function of time because of the changing elevation. An average array gain of 2.3 +/- 0.1 dB was observed, compared to an 2.4 dB theoretical improvement. The 0.1 dB difference is attributed to error in the correlation in the presence of noise as well as signal processing loss in the hardware. Laboratory measurement with calibrated test signal demonstrated that the SNR degradation effect in the hardware is at most 0.2 dB.

Figure 11 presents result from an array of maximum configuration. It employs all operational antennas available for X-band deep space support at Goldstone. The track was conducted with the Saturn-bound Cassini spacecraft on August 3, 1999. Relative to the performance of the 70-m antenna, the array yielded a gain of 1.8 dB, with 0.6 dB 1-sigma uncertainty Theoretical improvement would have been 1.98 dB.

Radiometric array gain

On the same July 1st track, ranging measurement was also obtained. Surprisingly, the realized gain for ranging is not the same as telemetry. A 1.6 +/- 0.3 dB gain was measured relative to 2.4 dB predicted. Among the possible causes is the fact that the frequency of ranging component lies much further away from the carrier, compared to the sideband frequency. In the presence of noise and ever changing Doppler frequency, the error in the phase and delay estimation of the 22.5 kHz sideband gets magnified when extrapolated to the 1 MHz ranging signal.

7. CONCLUSIONS

In summary, the paper discussed the array implementation recently carried out at the Jet Propulsion Laboratory. It presents a brief history of arraying and how this particular method of full spectrum arraying is beneficial, compared to other techniques. A general description of equipment and special considerations on signal processing is covered. The paper also presents most recent data collected from the field with Mars 98 Orbiter and Cassini spacecraft.

This new products enables the NASA Deep Space Network to provide better support to mission. It is now possible to provide extra performance in radiometric data, not just telemetry. Also, with the advances in digital signal processing, the delay within the new system is no longer subjected to the phase drift of analog components that are often seen with previous system. This, in turn, eliminates the need of long calibration at pre-track time, results in both a system easier to operate and with higher schedule utility.

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REFERENCES

[1] Dave Fort, Preliminary Design Review of Array Implementation, Jan. 1998.

BIOGRAPHY

Tim Pham *is member of technical staff at the Jet Propulsion Laboratory. He led the development of several systems, ranging from demonstration of carrier array, radio science, Galileo telemetry support and more recent 34-meter antenna arraying. He receives a BSEE from Caltech and a MSEE from University of Southern California.*

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Figure 2

Effective Array Gain (G/T)

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DESCANSO

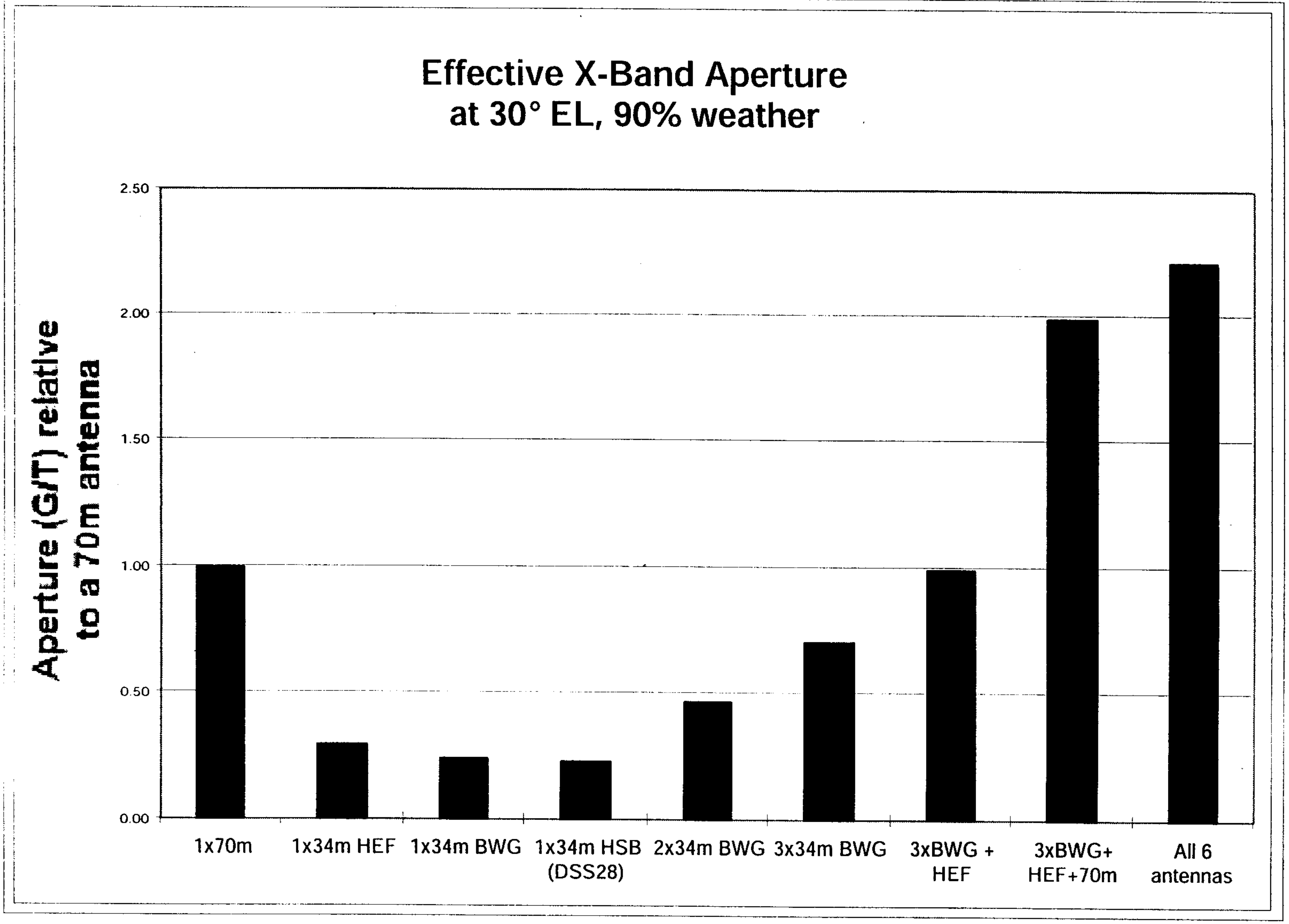

Figure 3

Array Signal Path

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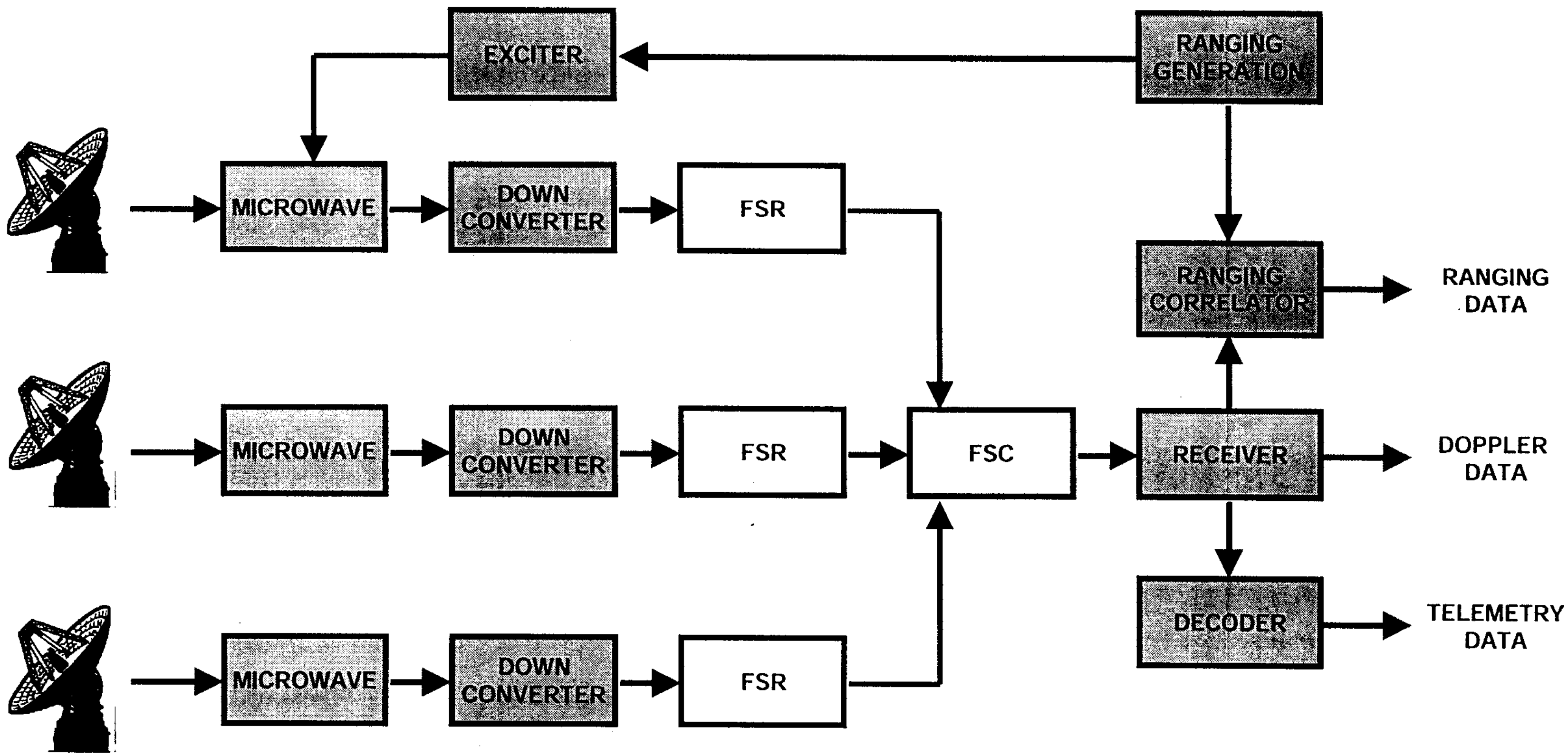

Figure 10

Two Antenna Arraying

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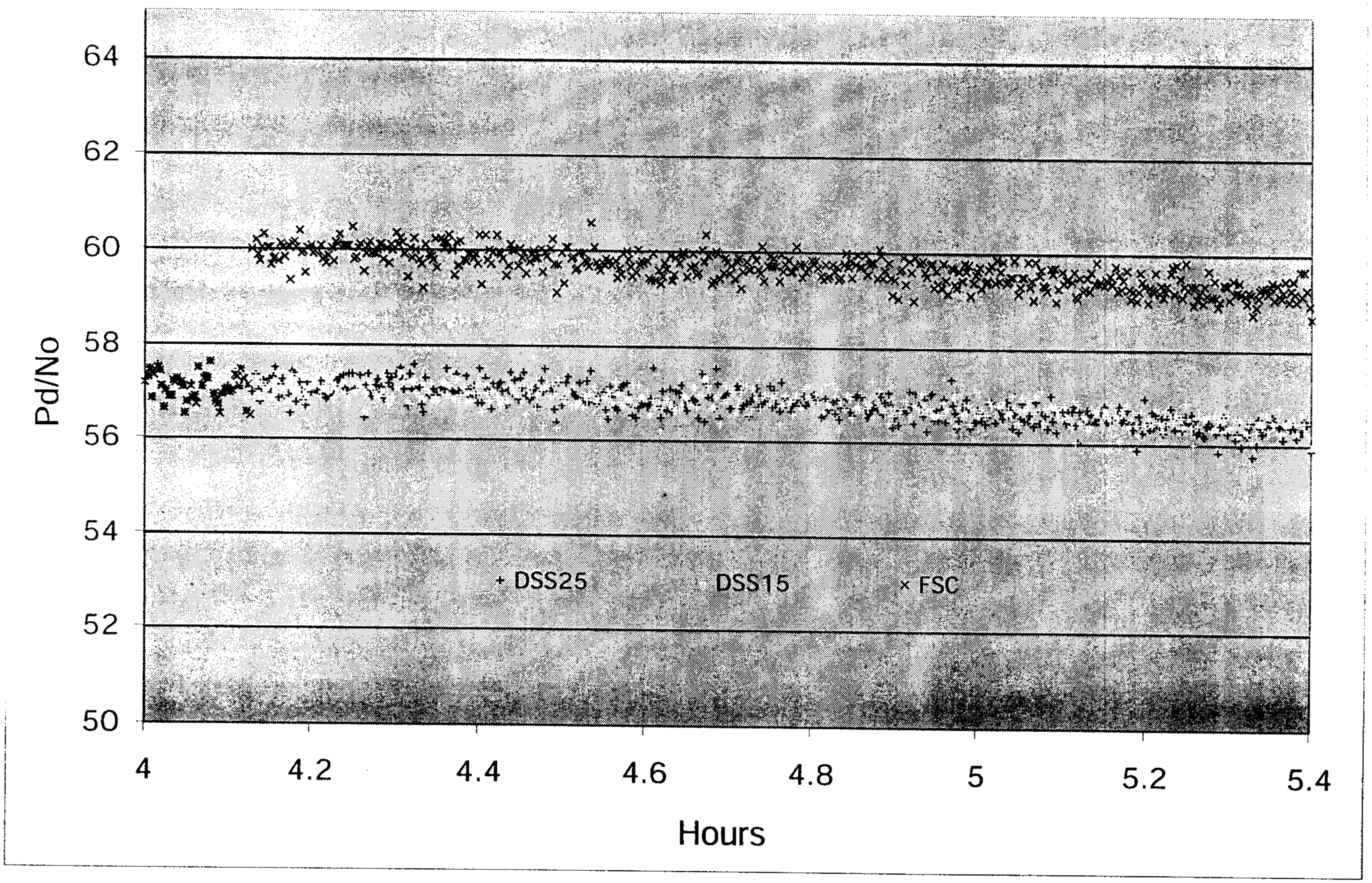

Figure 11

Four Antenna Arraying

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